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All-optical trapping methods are used to produce a strongly-interacting Fermi gas near a Feshbach resonance. The gas has universal properties, enabling table top experiments to explore diverse fermionic systems, ranging from high temperature superconductors to nuclear matter, neutron stars, and quark-gluon plasmas.

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1) K. M. O'Hara, S. L. Hemmer, S. R. Granade, M. E. Gehm, and J. E Thomas (with V. Venturi, E. Tiesinga, and C. J. Williams), "Measurement of the zero crossing in a Feshbach resonance of fermionic ^{6}Li," Phys. Rev. A **66**, Rapid Comm. 041401 (2002).
2) K. M. O'Hara, S. L. Hemmer, M. E. Gehm, S. R. Granade, and J. E. Thomas, "Observation of a strongly interacting degenerate Fermi gas of atoms," *Science* **298**, 2179 (2002).
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5) J. E. Thomas, S. L. Hemmer, J. Kinast, A. Turlapov, M. E. Gehm, and K. M. O'Hara, "Dynamics of a highly-degenerate, strongly-interacting Fermi gas of atoms," Proceedings of the Quantum Fluids Conference 2003 (Albuquerque, NM, August 3-8, 2003); J. Low Temp. Phys. **104** (2003).
6) J. E. Thomas, S. L. Hemmer, J. M. Kinast, A. V. Turlapov, M. E. Gehm, and K. M. O'Hara, "Dynamics of a highly-degenerate, strongly-interacting Fermi gas," Proceedings of the 16$^{\text{th}}$ International Conference on Laser Spectroscopy, (Palm Cove, Australia, July 13-18, 2003).

7) K. M. O'Hara, M. E. Gehm, S. R. Granade, M.-S. Chang, and J. E. Thomas, "Coherence in an optically trapped Fermi gas," in *Proceedings of the Eighth Rochester Conference on Coherence and Quantum Optics*, N. P. Bigelow, J. H. Eberly, C. R. Stroud, and I. A. Walmsley, editors, (Kluwer Academic/Plenum Publishers, New York, 2003), pp. 587.
8) J. Kinast, S. L. Hemmer, M. E. Gehm, A. Turlapov, and J. E. Thomas, "Evidence for superfluidity in a resonantly interacting Fermi gas," Phys. Rev. Lett. **92**, 150402 (2004).
9) J. E. Thomas and M. E. Gehm, "Optically trapped Fermi gases," Amer. Sci. **92**, 238-245 (2004).
10) J. Kinast, A. Turlapov, and J. E. Thomas, "Breakdown of hydrodynamics in the radial breathing mode of a strongly interacting Fermi gas," Phys. Rev. A **70**, 051401(R) (2004).
11) J. Kinast, A. Turlapov, and J. E. Thomas, "Heat capacity of a strongly-interacting Fermi gas," *Science* **307**, 1296 (2005).
12) J. Kinast, A. Turlapov, and J. E. Thomas,"Damping of a Unitary Fermi Gas," Phys. Rev. Lett. **94**, 170404 (2005).

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

J. E. Thomas
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M. E. Gehm (Graduate Student/Post doctoral associate) Ph. D. May, 2003.
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M. Brown (Undergraduate Student)

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None.

BRIEF OUTLINE OF RESEARCH FINDINGS

Overview

Optically-trapped, strongly-interacting Fermi gases exhibit universal behavior, and provide a model for exploring exotic systems in nature, from high-temperature superconductors to neutron stars and quark-gluon plasmas. Hence, the study of such gases is of great importance and of fundamental interest. In atomic Fermi gases, strong interactions are produced in the vicinity of a Feshbach resonance, where a bound molecular state in a closed exit channel is magnetically tuned into coincidence with the total energy of a pair of colliding particles. In this case, the zero energy scattering length a_S, which characterizes the interactions at low temperature, can be tuned through $\pm\infty$. Hence, such systems are ideal for exploring matter wave interactions in the strongly-interacting regime. For very large values of $|a_S|$, the important properties of the system (e.g., the effective mean field potential, the collision rate, the superfluid transition temperature, etc.) lose their dependence on the magnitude and sign of a_S, and instead become proportional to the the Fermi energy with different universal proportionality constants. For this reason, tabletop experiments with strongly interacting atomic Fermi gases can provide measurements that are relevant to all strongly-interacting Fermi systems, thus impacting theories in intellectual disciplines outside atomic physics, including materials science and condensed matter physics (superconductivity), nuclear physics (nuclear matter), high-energy physics (effective theories of the strong interactions), astrophysics (compact stellar objects, neutron stars), quark-gluon plasma physics (elliptic flow), and string theory (minimum viscosity hydrodynamics).

During the period of this grant, we have had several major breakthroughs. We were the first group in the world to produce a strongly-interacting, degenerate Fermi gas in 2002. We made the first observations of the anisotropic hydrodynamic expansion of the cloud at very low temperature, which was suggestive of superfluidity, but did not provide a conclusive proof. In 2004, we excited the breathing mode and obtained the first evidence for superfluid hydrodynamics. In 2005, we made the first thermodynamic measurements, i.e., we measured the heat capacity of the gas, which revealed a phase transition. In 2005, we also measured the damping rate of the breathing mode as a function of empirical temperature, and observed a transition in behavior. These results is described briefly below.

A. Observation of a Strongly-Interacting, Degenerate Fermi Gas

[O'Hara et al., *Science* **298**, 2179 (2002)]

In 2002, we prepared and studied for the first time, a highly-degenerate, strongly-interacting Fermi gas of ^{6}Li. In the experiments, a 50-50 mixture of spin-up and spin-down atoms was confined in an optical trap. A magnetic field was applied to tune the gas just above the center of a broad Feshbach resonance, producing strong-interactions, and the sample was then cooled by direct evaporation in the optical trap.

Upon release from the cigar-shaped optical trap, the gas was observed to expand anisotropically, standing nearly still in the originally long direction, while expanding rapidly in the originally narrow direction, inverting the aspect ratio. At the very lowest temperatures, this behavior was suggestive of superfluidity, since Pauli blocking suppresses collisions. However, it was suggested by the MIT group that deformation of the Fermi surface during expansion, and subsequent collisional hydrodynamics, could not be ruled out. While subsequent theory showed that this scenario was unlikely, experimental proof was lacking. However, the paper was the first attempt to observe superfluidity, and provided the first signs of superfluidity in a Fermi gas. The paper is now frequently cited in the context of high-temperature superconductivity, which arises from strong spin pairing.

In O'Hara et al., similar anisotropic expansion was also observed at higher temperatures and ascribed to unitary collision dynamics, which was a central point of the paper. This behavior is currently of great interest in the quark-gluon plasma community, where the paper is frequently cited as an example of "elliptic flow," which is believed to be a characteristic of a quark-gluon plasma. It is also referenced in the context of string-theory, as an example of minimum viscosity hydrodynamics, which arises in scale-invariant, universal systems.

Additional accomplishments of the 2002 paper include the introduction and first measurement of a universal interaction parameter, which is of great interest in the nuclear physics and neutron star communities.

B. Evidence for High Temperature Superfluidity in a Strongly Interacting Fermi Gas. [Kinast et al., Phys. Rev. Lett. **92**, 150402 (2004)]

We also made the first collective mode measurements in a strongly-interacting Fermi gas. The purpose was to obtain evidence for superfluid hydrodynamics in the *trapped* gas, eliminating the criticism of our 2002 paper, that deformation in the Fermi surface during expansion might have resulted in collisional hydrodynamics.

Study of collective modes provides a means of probing the dynamics of quantum gases, and can provide important information about the equation of state as well as evidence for superfluidity.

We excited the radial breathing mode of the gas by briefly turning off the trap and then recapturing the atoms. The atoms expand slightly, and when the trap is turned back on, the atoms have a higher potential energy than initially. The gas is permitted to oscillate radially in and out for a variable hold time, t_0. Then the cloud is released and imaged after 1 ms. The temperature is estimated by fitting a Thomas-Fermi distribution to the cloud shape to extract the zero temperature (Fermi) radius and the empirical reduced temperature $(T/T_F)_{fit}$, where T_F is the Fermi temperature for a noninteracting gas.

We observed a breathing mode frequency in precise agreement with predictions based on universal hydrodynamics, which arises near a Feshbach resonance. Evidence for superfluidity arose in the damping rate, which was found to decrease with decreasing empirical temperature in the highly degenerate regime. Since the gas is hydrodynamic, as shown by the frequency, in a normal fluid, one would expect the damping rate to be inversely proportional to the collision rate. Since the collision rate decreases with temperature in the degenerate regime where Pauli blocking is effective, one would expect the damping rate to increase with decreasing temperature for a normal fluid. Hence, the opposite behavior of the damping rate is indicative of superfluid hydrodynamics.

C. Heat Capacity in a Strongly Interacting Fermi Gas.

[Kinast et al., *Science* **307**, 1296 (2005)]

In studies of superfluidity and phase transitions in condensed matter, the measurement of the heat capacity has played a central role. For this reason, we devised the first experimental techniques to explore the heat capacity in a strongly interacting Fermi gas.

To accomplish this goal, two new techniques were developed. First, we devised a method for precisely adding energy to the gas. This is accomplished by releasing the gas for a short time. The cloud expands, and then the trap potential is reinstated, increasing the potential energy, and hence the total energy. While this idea is simple, new concepts arise in interpreting precisely how much energy is added, based on universal thermodynamics. Second, we make a one parameter empirical temperature measurement. This is accomplished by fitting a Thomas-Fermi profile (for a noninteracting gas) to the measured profile for the interacting gas. We hold the Fermi radius constant and fit only the reduced temperature parameter, which serves as an empirical temperature. This empirical temperature is calibrated by performing the same procedure on the theoretical spatial profiles.

The empirical temperature is measured as a function of total energy, and the plot of energy versus empirical temperature reveals an abrupt change in behavior, signalling a phase transition. After calibration, we find that the transition temperature is near 30% of the Fermi temperature, in very good agreement with recent predictions for the superfluid transition in a strongly-interacting Fermi gas.

D. Damping in a Strongly-Interacting Fermi Gas.
[Kinast et al., Phys. Rev. Lett. **94**, 170404 (2005)]

We have made the first comprehensive measurements of the damping rate and frequency of the radial breathing mode as a function of temperature, by using the empirical temperature measurement method described above. In the experiments, energy is precisely added to the gas, the empirical temperature is measured, and the breathing mode excited. The frequency remains close to the universal hydrodynamic value over a wide temperature range, while the damping rate reveals a transition in behavior, at a temperature close to that measured for the transition in the heat capacity. Hence, the heat capacity and damping experiments provide the first experimental determinations of the superfluid transition temperature in a strongly-interacting Fermi gas.

Invited Talks

During this period, our group presented 32 invited talks and colloquia discussing this research:

1) J. E. Thomas, "From Superconductors to Nuclear Matter: Degenerate Fermi gases as Analogs of Fundamental Systems," (Lawrence Berkeley Laboratory and Physics Department, Berkeley, CA Nov. 6, 2002).
2) J. E. Thomas, "Exploring Superconductors to Neutron Stars with a Degenerate, Fermi Gas of Atoms," Duke University (January 15, 2003).
3) Ken O'Hara and J. E. Thomas, "Experiments with a Strongly-Interacting Fermi Gas," BECQI'03 - Workshop on Bose-Einstein Condensation and Quantum Information (16-20 February 2003 Rydges Oasis Resort - Caloundra, Sunshine Coast Queens-

land, Australia), presented by Ken O'Hara.
4) J. E. Thomas, "All-Optical Production of a Strongly-Interacting, Degenerate, Fermi gas: A New Quantum Regime," Keithley Award Symposium, APS March Meeting, (March 5, 2003, Austin, TX).
5) J. E. Thomas, "Universal Behavior in a Strongly-Interacting Fermi Gas," Center for Ultracold Atoms, MIT (March 11, 2003).
6) J. E. Thomas, "Universal Dynamics in a Strongly Interacting Fermi Gas," Ohio State University (April 1, 2003).
7) J. E. Thomas, "Universal Dynamics in a Strongly Interacting Fermi Gas," Georgia Tech (April 9, 2003).
8) M. E. Gehm and J. E. Thomas, "Universal Dynamics of a Strongly-Interacting Fermi Gas," NASA Fundamental Physics meeting, (Oxnard CA, April 14-16, 2003), talk presented by M. Gehm.
9) J. E. Thomas, "Universal Dynamics in a Strongly-Interacting Degenerate Fermi Gas of Atoms," Atomic Physics Gordon Conference, Tilton School (Tilton, NH, June 15-20, 2003).
10) J. E. Thomas, "Universal Dynamics in a Strongly-Interacting Fermi Gas," ICOLS03: 16th International Conference on Laser Spectroscopy (Cairns, Australia, July 13-18, 2003).
11) J. E. Thomas, "Dynamics of a Highly-Degenerate, Strongly-Interacting Fermi Gas," QFS 2003: Quantum Fluids and Solids International Symposium, UNM (August 3-8, Albuquerque, NM).
12) J. E. Thomas, "Dynamics of a Highly-Degenerate, Strongly-Interacting Fermi Gas of Atoms," Bose-Einstein Condensation, EuroConference on the New Trends in Physics of Quantum Gases, San Feliu de Guixols, Spain (September 13-18, 2003).
13) J. E. Thomas, "Quantum Dynamics of Ultracold Fermionic Vapors," DOE Basic Energy Sciences-Atomic Molecular and Optical Physics Meeting, (Tahoe City, September 21-23, 2003).
14) J. E. Thomas, "Exploring Superconductors and Neutron Stars on a Desktop," NC State University (Raleigh, NC, October 13, 2003).
15) J. E. Thomas, "Exploring Superconductors and Neutron Stars on a Desktop using Ultracold Fermi Gases," Penn State University (State College, PA, October 30, 2003).
16) A. Turlapov and J. E. Thomas, "Experiments with a Strongly-Interacting Fermi Gas," Southeastern Section APS Meeting, (Wrightsville Beach, NC, Nov. 6-8, 2003), talk presented by A. Turlapov.
17) J. E. Thomas, "Hydrodynamics in a Degenerate, Strongly-Interacting Fermi Gas,"

Workshop on Ultra-Cold Fermi Gases, Levico (Trento, Italy March 4-6, 2004).
18) J. E. Thomas, “Experiments with a Strongly-Interacting Degenerate Fermi Gas,” U. Wisconsin, Madison (March 12, 2004).
19) J. E. Thomas, “Experiments with a Strongly-interacting Degenerate Fermi Gas,” Wake Forest University (April 1, 2004).
20) J. E. Thomas, “Hydrodynamics in a Degenerate, Strongly Attractive Fermi Gas,” 2004 NASA/JPL Workshop on Physics for Planetary Exploration (Solvang, CA, April 20-24, 2004).
21) J. E. Thomas, “Hydrodynamics in a Degenerate, Resonantly Interacting Fermi Gas,” Quantum Gases Conference (KITP, Santa Barbara, CA, May 10-14 (2004).
22) J. E. Thomas, “Optically-Trapped, Strongly-Interacting Fermi Gases,” U. Texas Austin (Austin, Texas, September 29, 2004).
23) J. E. Thomas, “Optically-Trapped, Degenerate Fermi Gases as Paradigms for Strong Interactions,” APS Fall Meeting, Division of Nuclear Physics (Chicago, October 27-30, 2004).
24) J. E. Thomas, “Strongly-Interacting Cold Atoms,” Strongly Coupled Plasmas: Electromagnetic, Nuclear and Atomic, a RIKEN-BNL workshop, (Brookhaven, NY, December 16-17 2004).
25) J. E. Thomas, “Optically-Trapped, Strongly-Interacting Fermi Gases,” Old Dominion University (Norfolk, Va, February 8, 2005).
26) J. E. Thomas, “Superfluidity in a Strongly-Interacting Fermi Gas” APS March Meeting, (March 22, 2005), talk given by A. Turlapov.
27) J. E. Thomas, “High-Temperature Superfluidity in Ultracold Fermi Gases,” University of Chicago (Chicago, Ill, March, 29, 2005).
28) J. E. Thomas, “High-Temperature Superfluidity in Ultracold Fermi Gases,” U. Virginia (Charlottesville, Va, April 1, 2005).
29) J. E. Thomas, “High-Temperature Superfluidity in Ultracold Fermi Gases,” NYU (New York, NY, April 7, 2005).
30) J. E. Thomas, “High-Temperature Superfluidity in Ultracold Fermi Gases,” Columbia University, (New York, NY, April 11, 2005).
31) J. E. Thomas, “Thermodynamics of Strongly-Interacting Fermi Gases,” Workshop on Strongly Interacting Quantum Gases, Ohio Center for Theoretical Science, Ohio State University (Columbus, Ohio, April 18-21, 2005).
32) J. E. Thomas, “Thermodynamical and Mechanical Properties of a Strongly-Interacting Fermi Gas,” 17th International Conference on Laser Spectroscopy (Aviemore, Scotland, June 19-24, 2005).

Highlights of (or including) our Research

We wrote a popular article (by John Thomas and Mike Gehm):

1) American Scientist, "Optically Trapped Fermi Gases," May-June 2004, pp. 238-245.

2) The *First International Workshop on Ultracold Fermi Gases* was be held in Trento, Italy on March 4-6, 2004. The organizers made a poster to advertise the conference, and chose the anisotropic expansion data from our *Science* paper for the poster.

Published highlights since July, 2002 which are about or include our work:

1) Wissenschaft-online, on Anistropic Expansion, November 14, 2002.

2) "Optically Trapped Gas Offers Superconductivity Test Bed," Photonics Spectra **36**, 20 (December, 2002).

3) "All-Optical Trapping of a Degenerate Fermi Gas," AIP Physics News in 2002, 5 (February, 2003).

4) "A Strongly Interacting Degenerate Fermi Gas," Physics Today **56**, 9, Physics Update (March, 2003).

5) "The Next Big Chill," Scientific American **289**, 26, News Scan (October, 2003).

6) "Ultracold Fermionic Atoms Team Up as Molecules: Can They Form Cooper Pairs as Well?," Physics Today **56**, 18 (October, 2003).

7) "Fermi Gases Approach Superfluid Regime," Physics Web, April 15, 2004.

8) "Wobbly Jelly May Open Superconductor Door," News in Science, Australian Broadcasting Company, ABC Science Online, April 15, 2004.

9) "First Evidence for Superfluidity in an Atom-Based Fermi Gas," AIP Physics News Update, April 13, 2004.

10) “Cabouge du ct des fermions,” Info Science, May 24, 2004.

11) “Proof of New State of Matter is in the Jelly,” Jet Propulsion Laboratory Press Release, April 24, 2004.

12) Duke University Press Release, “ Supercold, Wiggling ’Jelly’ Presents Evidence of New Kind of Superfluidity,” April 13, 2004.

13) “First Evidence for Superfluidity in an Atom-Based Fermi Gas,” AIP Physics News in 2004 (February, 2005).

14) “Extreme Impersonations,” Science News **166**, 186, (September 18, 2004) (Cover).

15) “Lithium Flows Free,” Nature Research Highlights, Nature, **423**, (May 22, 2005).

16) Duke University Press Release, “Heat Response Suggests High-Temperature Superfluidity in exotic ultracold ’fermion’ Gas,” (January 27, 2005).

17) “Superfluidity in Fermi gases,” Physics World **18**, 43 (March 2005).

18) “Images of Vortices Reveal Superfluidity in a Fermi Gas,” Physics Today **58**, 25 (July, 2005).

19) “Thermodynamic Evidence for Fermi Superfluidity,” AIP Physics News Graphics (July 5, 2005).

20) “A String-Theory Calculation of Viscosity Could Have Surprising Applications,” Physics Today **58**, 23 (May, 2005).

Technological Applications

Our current experiments explore the dynamics of an ultracold, trapped fermionic vapor of ^{6}Li. These studies enable investigation of the strong Cooper pairing in a strongly interacting vapor with tunable interactions. ^{6}Li has recently been shown to be the highest temperature superconductor known, when the transition temperature is measured in units of the Fermi temperature. Hence, studies in this system are likely to lead to new and fundamental insights into the nature of high temperature superconductivity which strongly impacts materials science. Further, our ultrastable CO_2 laser enables trapping of both atoms and molecules with broad applications to precision measurements and novel clocks. For example, new clocks can be based on coherent superposition states of fermions which are prevented from colliding by the exclusion principle. Our experiments are also well suited for exploring novel matter-wave-optical processes, such as abrupt transitions between interacting and noninteracting states on a time scale short compared to the time over which an atom travels a de Broglie wavelength. In this case, novel many body quantum dynamics is expected. Such experiments will enable unique studies of nonlinear atom-wave processes, enabling new techniques for manipulation and control of matter-wave fields with applications in nanolithography.